Autonomous Assembly of a Team of Flexible Spacecraft

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Summary. This lecture presents the recent studies of authors on the autonomous assembly for a team of flexible spacecraft on orbit via dynamic modeling, theoretical analysis, numerical simulations and experimental verifications. The lecture starts with the proper dynamic modeling of a rigid spacecraft with a flexible appendage. To realize the autonomous assembly of a team of such spacecraft at their flexible appendage tips, the lecture presents an integrated controller with an output consensus control and a collision avoidance control. The autonomous assembly includes following steps: to regulate the attitudes of the spacecraft synchronously, to drive the spacecraft to a pre-assembly configuration and to assemble all spacecraft together. The collision avoidance controller should work in the first two steps to drive the team members to the target configuration without any inter-member collisions. The lecture also presents a novel distributed controller based on an artificial potential field for the autonomous assembly of above flexible spacecraft without inter-member collision. Finally, the lecture demonstrates the experimental validations of autonomous assembly of two spacecraft simulators with air-bearings on a test-bed via the above controllers.

Introduction

The autonomous assembly of two or more spacecraft on orbit is an appealing technology for future space missions [1,2] since it is able to construct large space systems, such as a space telescope and a solar power station, on orbit. However, the on-orbit assembly is facing many challenges. For example, the spacecraft to be assembled may have very flexible appendages. Thus, the coupled overall motion of the spacecraft body and the vibration of the flexible appendages greatly increase the difficulty of state consensus of spacecraft in assembly. Furthermore, the autonomous assembly of a team of spacecraft is far different from their attitude synchronization or formation flying. The distance between any two teammates in the assembly may be so small that the inter-member collision has to be avoided.

The objective of this lecture is to present a new controller of state consensus and collision avoidance for the autonomous assembly of a team of spacecraft with flexible appendages. The lecture gives the dynamic modeling, the design of controllers, the numerical simulations and experimental validations consequently.

Theoretical Studies

Dynamic model for a team of flexible spacecraft

The spacecraft of concern has a rigid body and a flexible appendage. Fig. 1 shows two spacecraft simulators, each of which has a thin plate appendage and can be simplified as a hub-beam model in Fig. 2. Previous studies show that the dynamics of a hub-beam model can be described via the fundamental modal coordinate p of the appendage in a floating frame *oxy* attached to the hub and the coordinates (X_0, Y_0, θ) of hub in an absolute frame *OXY* if the hub rotation is slow and the appendage deformation is small. These conditions are valid for most assembly procedures.

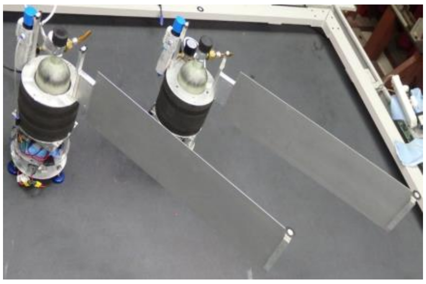


Fig. 1 Two spacecraft simulators floating on a marble test-bed.

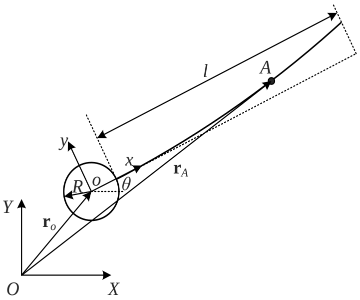


Fig. 2 A hub-beam model for a spacecraft with a flexible appendage.

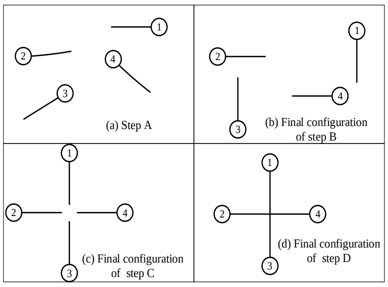


Fig. 3 An autonomous assembly procedure of *N* hub-beam models.

Procedure of an autonomous assembly

As shown in Fig. 3, the autonomous assembly procedure of *N* hub-beam models can be divided into four steps. At step A, the hub-beam models in a ring topology are numbered as follows: i.e., the topmost one is numbered as 1, the others are numbered, in anticlockwise, as 2, …, *N*. At step B, the attitudes of the *N* hub-beam models are regulated to a synchronous status. At step C, they are driven to a pre-assembly configuration. Finally, they are assembled together at step D. It is essential to design a controller for steps B and C so that the hub-beam can not only get proper status, but also avoid any possible collisions. This is not an easy task since each hub-beam model is under-actuated because the control forces can only be applied to the hub.

Design of controllers

As proved by Lyapunov analysis in [3], the output consensus of the team can be achieved via the following controller

$$\begin{cases}\mathbf{s}_i = \boldsymbol{\lambda}\mathbf{y}_i + \mathbf{z}_i, \\ \boldsymbol{\tau}_i = -\mathbf{K}_1\mathbf{s}_i + \mathbf{K}_2\mathbf{s}_{i-1} + \mathbf{K}_2\mathbf{s}_{i+1};\end{cases} \qquad \mathbf{y}_i = \begin{bmatrix} X_{0i} + (R_i + l_i)\cos\theta_i \\ Y_{0i} + (R_i + l_i)\sin\theta_i \\ \theta_i - 2\pi(i - N/2)/N \end{bmatrix}, \quad \mathbf{z}_i = \begin{bmatrix} \dot{X}_{0i} \\ \dot{Y}_{0i} \\ \dot{\theta}_i \end{bmatrix}, \quad i = 1, 2, 3, N.$$

where $\mathbf{y}_i$ and $\mathbf{z}_i$ are the position and velocity vectors of the *i*-th hub-beam model, $\boldsymbol{\tau}_i$ is the corresponding control force vector, $\mathbf{K}_1$ and $\mathbf{K}_2$ are two gain matrices yielding $\mathbf{K}_1 > 2\mathbf{K}_2$ for $N \geq 3$ or $\mathbf{K}_1 > \mathbf{K}_2$ for $N = 3$.

To avoid any possible collisions of two hub-beam models in assembly, it is easy to define their outlines via circles and ellipses shown in Fig. 4 and introduce an artificial potential for collision avoidance

$$V_{av} = \eta\left[\exp(-\gamma d_{H1H2})/d_{H1H2} + \exp(-\gamma d_{H1B2})/d_{H1B2} + \exp(-\gamma d_{H2B1})/d_{H2B1} + \exp(-\gamma d_{B1B2})/d_{B1B2}\right]$$

where η and γ are two positive parameters, d_{JK} is the distance between curves *J* and *K* in Fig. 4. Then, the control force for the collision avoidance reads $\mathbf{f}_{av} = -\partial V_{av} / \partial \mathbf{q}$.

Furthermore, it is possible to design a controller based on the artificial potential, which mainly depends on the attitude error between a hub-beam model and its neighbor, the radial Euclidian distance between the ellipse and the circle, and the classical Euclidian distance between the centers of the ellipse and the circle. As proved in [4], the Lyapunov analysis guarantees that the hub-beam models asymptotically converge to the target configuration.

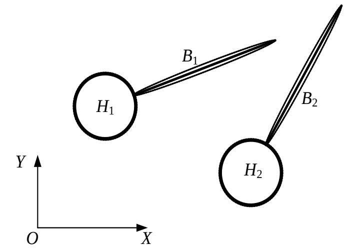
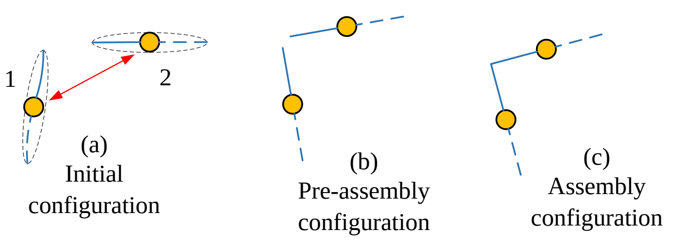


Fig. 4 Outlines of two hub-beam models.



(a)
Initial
configuration

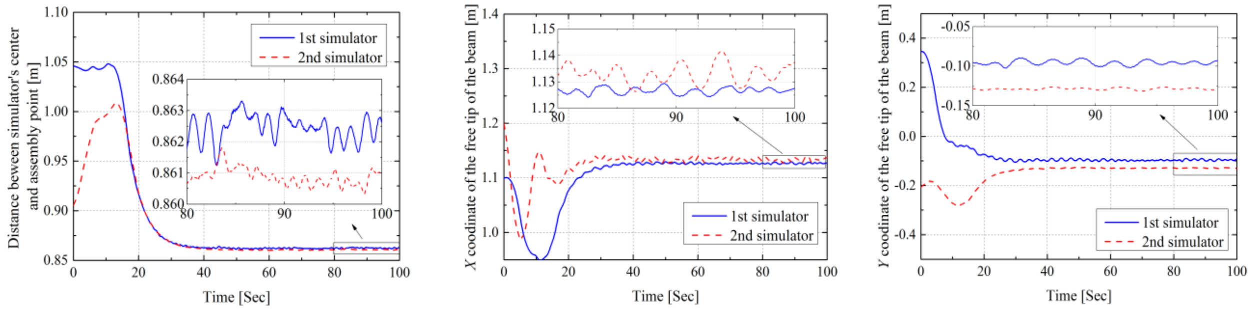
(b)
Pre-assembly
configuration

(c)
Assembly
configuration

Fig 5. An autonomous assembly of two spacecraft simulators at their appendage tips.

Experimental Studies

A test rig was established at the lab of authors to perfome the autonomous assembly of two spacecraft simulators at their appendage tips as shown in Fig. 5. The two spacecraft simulators were floating on a marble test-bed via air bearing as shown in Fig. 1. During the assembly, the position and velocity of each simulator were sensed by an optical measurement on the lab ceiling and sent to a computer to generate control signals, which returned to the simulator via a wireless network and adjusted the air flow to drive the simulators. Fig. 6 presents the measured positions of two spacecraft simulators under the control of artificial potential and well validates the efficacy of designed controller.



a. Distance from the spacecraft simulator center to the appendage tip

b. Position of appendage tip in *X* direction

c. Position of appendage tip in *Y* direction

Fig. 6 Measured positions of two spacecraft simulators assembled at their appendage tips

Concluding Remarks

Both numerical simulations and experimental studies show that the new controller of state consensus and collision avoidance proposed is able to realize the autonomous assembly of a team of spacecraft with flexible appendages. The on-going research is to reduce test errors in autonomous assembly.

References

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